

MEMORANDUM REPORT ARBRL-MR-03237

STORED ENERGY AND PLASTIC VOLUME CHANGE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) In this brief note it is pointed out that a relation between stored energy of plastic work and volume change, as derived by Toupin and Rivlin (1960), is borne out remarkably well in the case of four metals for which sufficient data exist in the literature. Some conditions that should enhance volume change are pointed out, and partial data for six other metals are tabulated.		

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I. BACKGROUND

In 1960 Toupin and Rivlin¹ published a paper in which it was shown that plastic deformation, stored in the form of dislocations, causes a volume change or equivalently a density change in crystalline materials. The calculation is based on second order nonlinear elasticity and assumes only that the material is essentially the same throughout the body and that the surface of the body is free of stress, but that there are residual stresses in the interior. The deformation path is immaterial since comparisons are made only between the perfect crystal lattice and the final configuration of dislocations. The dislocations give rise to self-equilibrated internal stresses, and the stresses, in turn, give rise to stored elastic energy. It is this energy which is called "the stored energy of plastic deformation" or simply "stored energy" in the rest of this note.

The derivations are made for arbitrary anisotropy, but then specialized for cubic materials. The principal result is a relation between volume change and stored energy. The following is eqn. (7.2) from Toupin and Rivlin¹ with a slight rearrangement of terms.

$$k \frac{(V-V_0)/V_0}{\int W dV_0/V_0} = \left(\frac{\partial k}{\partial p} - 1 \right) R_D + \left(\frac{k}{\mu} \frac{\partial \mu}{\partial p} - 1 \right) R_S + \left(\frac{k}{\nu} \frac{\partial \nu}{\partial p} - 1 \right) R_{S'} \quad (1)$$

Eqn. (1) states that the fractional volume change, divided by the stored energy per unit volume, is determined by a certain weighted sum whose terms depend on elastic moduli and pressure derivatives of elastic moduli. The bulk modulus is k , and μ and ν are shear moduli. In terms of second order moduli, as defined by Brugger² and listed for many materials in Hearman³, these are given as follows.

$$k = \frac{1}{3} (c_{11} + 2 c_{12}), \quad \mu = \frac{1}{2} (c_{11} - c_{12}), \quad \nu = \frac{1}{2} (c_{11} - c_{12}) - c_{44}. \quad (2)$$

The pressure is p , and all moduli and pressure derivatives of moduli are evaluated at zero pressure. The total strain energy density W is the sum $W_D + W_S + W_{S'}$, where each term is quadratic in strain and depends on only one of the three constants in eqn. (2).

¹R. A. Toupin and R. S. Rivlin (1960), "Dimensional Changes in Crystals Caused by Dislocations," *J. Math. Phys.* 1, 8.

²K. Brugger (1964), "Thermodynamic Definition of Higher Order Elastic Coefficients," *Phys. Rev.* 133, A1611.

³R. F. S. Hearman (1979), "The Elastic Constants of Crystals and Other Anisotropic Materials," and "The Third- and Higher-Order Elastic Constants," *Elastic, Piezoelectric, and Related Constants of Crystals*, Landolt-Börnstein, New Series III/11, K.-H. Hellwege (Ed. in Ch.), Springer, New York, Ch. 1 and 2.

$$W_D = \frac{1}{2} k(e_{ij})^2, \quad W_S = \mu e'_{mn} e'_{mn}, \quad W_{S'} = \nu(e_{12}^2 + e_{23}^2 + e_{31}^2) \quad (3)$$

In eqns. (3) e_{ij} is strain, e'_{ij} is deviatoric strain, and in the third of eqns. (3) the components of strain are referred to the principal cubic axes. The numbers R_D , R_S , and $R_{S'}$ are fractions of the total stored energy, defined as follows.

$$R_D = \int W_D dV_0 / \int W dV_0, \quad R_S = \int W_S dV_0 / \int W dV_0, \quad R_{S'} = \int W_{S'} dV_0 / \int W dV_0 \quad (4)$$

Formula (1) is very appealing in that it relates volume change directly to stored energy, elastic moduli, and pressure derivatives of moduli without calculation of the energy of single dislocations or dislocation interactions, core sizes or effective ranges of dislocations, or total numbers and lengths of dislocations. Furthermore, review of the derivation in Toupin and Rivlin¹ shows that the formula should apply to polycrystalline materials, as well as crystals, and to twins and stacking faults, as well as dislocations, since in each case tractions are continuous across all material boundaries, and the material everywhere is still essentially the same.

On the other hand, other factors that affect volume changes, such as point defects or order/disorder transitions are not so easily accommodated. Equation (1) also shows that there is unlikely to be a linear relation between volume change and stored energy since the three ratios R_D , R_S , and $R_{S'}$ need not be fixed, but may change during deformation or annealing. The formula does supply bounds, however, as has been pointed out in Toupin and Rivlin¹, since $R_D + R_S + R_{S'} = 1$.

II. COMPARISONS MADE FROM EXISTING DATA

To test the validity of the formula it is necessary to make independent measurement of the stored energy of plastic deformation and the corresponding density change, and to have available the appropriate second order elastic moduli and either the pressure derivatives of those moduli or the third order moduli from which the pressure derivatives may be calculated.

The stored energy of cold work has been a topic of considerable interest to metallurgists for some time, e.g., see Bever, Holt and Titchener⁴, but of

⁴M. B. Bever, D. L. Holt, and A. L. Titchener (1973), "The Stored Energy of Cold Work," Prog. Mat. Sci. 17.

all the work that has been done only that by Clarebrough and co-workers^{5,6,7,8} seems to have included both stored energy and density change for the same materials. Data exist for Ag, Au, Cu, and Ni. Second and third order elastic moduli, as well as pressure derivatives of second order moduli, exist for those same materials and also for many other metals, alloys, and compounds (Hearman³).

In dimensionless terms, Table I compares measured values of the left hand side of eqn. (1) with computed values of the terms in parentheses on the right hand side of eqn. (1). Measured values of stored energy and density change are taken from the work of Clarebrough, et al.^{5,6,7,8}, and computed values are calculated from data listed in Hearman³.

TABLE I
COMPARISON OF CALCULATED AND MEASURED TERMS IN EQUATION (1)

	Calculated Values			Measured	Remarks
	$\frac{\partial k}{\partial p} - 1$	$\frac{k}{\mu} \frac{\partial \mu}{\partial p} - 1$	$\frac{k}{v} \frac{\partial v}{\partial p} - 1$	$k \frac{\Delta V/V_o}{\int W dV_o/V_o}$	
Ag	4.82	3.12	4.20	3.72	$\epsilon = 0.75$, compression
Au	5.22	3.64	7.75	6.70	$\epsilon = 0.75$, compression
Cu	4.34	2.14	3.63	3.52	$\epsilon = 0.3$, compression
				3.96	$\epsilon = 0.55$, compression
				4.79	$\epsilon = 0.70$, compression
Ni	4.14	1.32	3.54	3.71	$nd/\ell = 1.41$, torsion
				3.78	$nd/\ell = 2.46$, torsion

⁵L. M. Clarebrough, M. E. Hargreaves, and G. W. West (1955), "The Release of Energy During Annealing of Deformed Metals," *Proc. Roy. Soc. Lond. A* 232, 252.

⁶L. M. Clarebrough, M. E. Hargreaves, and G. W. West (1956), "Density Changes During the Annealing of Deformed Nickel," *Phil. Mag.* 1, 528.

⁷L. M. Clarebrough, M. E. Hargreaves, and G. W. West (1957), "The Density of Dislocations in Compressed Copper," *Acta Met.* 5, 738.

⁸L. M. Clarebrough, M. E. Hargreaves, and M. H. Loretto (1962), "Electrical Resistivity of Dislocations in Face-Centered Cubic Metals," *Phil. Mag.* 7, 115.

III. DISCUSSION

In every case, except for Cu at the highest level of strain, the measured value of volume change per unit of stored energy falls well within the bounds calculated from elastic moduli and pressure coefficients. Thus, it would appear that the actual volume change that occurs during plastic deformation of a metal depends to a considerable extent on the amount of plastic work which is actually stored as cold work. The amount stored depends in turn on the amount of plastic work done on the material and the percentage stored.

In view of the preceding comments, high strength, fine grained alloys should be likely candidates to show a pronounced volume change under plastic deformation since high strength requires more plastic work for a given strain increment, and small grain size and the presence of alloying elements tend to block the motion of dislocations hence promoting higher densities of dislocations and a higher percentage of cold work stored. Unfortunately, there are few reliable data in the literature on plastic volume change for high strength alloys (see Reference 9), and none for either large strains or for which stored energy has also been measured. In fact, stored energy measurements on heat treatable alloys seem to be almost totally lacking, Bever, et al⁴.

Table II lists six other cubic metals for which data on elastic constants and pressure coefficients are available from Hearman³, but for which no reliable data seem to exist for both density change and stored energy from plastic deformation. Where multiple values were given, simple averages have been used. There appears to be considerable variation in the data, but the sample sizes are small so no attempt has been made to estimate overall error bands.

TABLE II
CALCULATED VALUES FOR OTHER METALS

	$\frac{\partial k}{\partial p} - 1$	$\frac{k}{\mu} \frac{\partial \mu}{\partial p} - 1$	$\frac{k}{v} \frac{\partial v}{\partial p} - 1$
Al	4.46	4.52	9.91
Fe	4.62	2.82	2.67
Ge	3.70	-0.36	1.80
Pb	4.43	2.79	5.75
Nb	4.40	1.85	3.09
Ta	2.44	2.66	-0.95

⁹O. Richmond and W. A. Spitzig (1980), "Pressure Dependence and Dilatancy of Plastic Flow," *Proceedings of the XV International Congress of Theoretical and Applied Mechanics*, F. P. J. Rimrott and B. Tabarrok (Ed.), North Holland, New York.

Because of its low bulk modulus (about 77 GPa) and its high pressure coefficients, as shown in Table II, Al should show a relatively large plastic volume change. Conversely, because of high bulk modulus (about 191 GPa) and low coefficients in Table II, Ta should show a relatively small plastic volume change.

It would seem that further experimental investigation of the relationship between plastic deformation and volume change is called for. In the mathematical theory of plasticity it is usually assumed that there is no plastic volume change, but there has been no systematic exploration of the issue. Because actual relative volume changes are small, they are difficult to measure, but given their fundamental importance for the theory of plastic deformation, the effort required should be well worthwhile.

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